

# A QCD analysis of ZEUS data including DIS inclusive cross sections with longitudinally polarised leptons and data run at lower proton beam energies.

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New ZEUS data are added into the NLO QCD analysis of the ZEUS-JETS PDF fit. The addition of high- $Q^2$  NC and CC  $e^-p$  inclusive cross-section data improves the determination of the  $u$ -valence quark at high  $x$ . The addition of high- $Q^2$  CC  $e^+p$  inclusive cross-section data improves the determination of the  $d$ -valence quark at high  $x$ . The addition of lower- $Q^2$  NC  $e^+p$  inclusive cross-section data, run at three different proton beam energies, improves the determination of the sea and gluon PDFs at small  $x$ . The new PDF fit is called the ZEUS09 PDF fit.

## 1 Introduction

The kinematics of deep inelastic lepton hadron scattering (DIS) is described in terms of the variables  $Q^2$ , the negative invariant mass of the exchanged vector boson, Bjorken  $x$ , the fraction of the momentum of the incoming nucleon taken by the struck quark (in the quark-parton model), and  $y$  which measures the energy transfer between the lepton and hadron systems. The double differential cross-sections for the neutral current (NC) process with lepton polarization  $P$  are given by,

$$\frac{d^2\sigma(e^\pm p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} [H_0^\pm + PH_P^\pm], \quad H_{0,P}^\pm = Y_+ F_2^{0,P} - y^2 F_L^{0,P} \mp Y_- x F_3^{0,P} \quad (1)$$

where,  $Y_\pm = 1 \pm (1-y)^2$ , and, at LO in QCD, the structure functions  $F_2^{0,P}$  and  $x F_3^{0,P}$  are directly related to quark distributions by

$$F_2^{0,P} = \sum_i x(q_i + \bar{q}_i) A_i^{0,P}, \quad x F_3^{0,P} = \sum_i x(q_i - \bar{q}_i) B_i^{0,P} \quad (2)$$

The coefficients  $A_i^0, B_i^0$  for unpolarised beams are given by

$$A_i^0(Q^2) = e_i^2 - 2e_i v_i v_e P_Z + (v_e^2 + a_e^2)(v_i^2 + a_i^2) P_Z^2 \quad (3)$$

$$B_i^0(Q^2) = -2e_i a_i a_e P_Z + 4a_i v_i v_e a_e P_Z^2 \quad (4)$$

The coefficients for the polarisation terms are given by

$$A_i^P = 2e_i a_e v_i P_Z - 2a_e v_e (v_i^2 + a_i^2) P_Z^2, \quad (5)$$

$$B_i^P = 2e_i a_i v_e P_Z - 2a_i v_i (v_e^2 + a_e^2) P_Z^2. \quad (6)$$

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The term in  $P_Z$  arises from  $\gamma Z^0$  interference and the term in  $P_Z^2$  arises purely from  $Z^0$  exchange, where  $P_Z$  accounts for the effect of the  $Z^0$  propagator relative to that of the virtual photon, and is given by

$$P_Z = \frac{Q^2}{Q^2 + M_Z^2} \frac{1}{\sin^2 2\theta_W}. \quad (7)$$

The other factors in the expression for  $A$  and  $B$  are the charge,  $e_i$ , NC electroweak vector,  $v_i$ , and axial-vector,  $a_i$ , couplings of quark  $i$  and the corresponding NC electroweak couplings of the electron,  $v_e, a_e$ . Equations 5,6 show that polarization effects are only important at high  $Q^2$ .

Unpolarized HERA data have been used in fits to determine Parton Distribution Functions (PDFs). For low  $x$ ,  $x \leq 10^{-2}$ ,  $F_2^0$  is sea quark dominated and its  $Q^2$  evolution, as predicted by QCD, is controlled by the gluon contribution, such that HERA data provide crucial information on low- $x$  sea-quark and gluon distributions. At high  $Q^2$ , the structure function  $xF_3^0$  becomes increasingly important, and gives information on valence quark distributions. The charged current (CC) interactions also enable separation of the flavour of the valence distributions at high- $x$ , since their (LO) cross-sections are given by,

$$\begin{aligned} \frac{d^2\sigma(e^+p)}{dx dQ^2} &= (1 + P) \frac{G_F^2 M_W^4}{(Q^2 + M_W^2)^2 2\pi x} x [(\bar{u} + \bar{c}) + (1 - y)^2(d + s)], \\ \frac{d^2\sigma(e^-p)}{dx dQ^2} &= (1 - P) \frac{G_F^2 M_W^4}{(Q^2 + M_W^2)^2 2\pi x} x [(u + c) + (1 - y)^2(\bar{d} + \bar{s})]. \end{aligned}$$

Parton Density Function (PDF) determinations are usually global fits [2, 3, 4], which use fixed target DIS data as well as HERA data. In such analyses, the high statistics HERA NC  $e^+p$  data have determined the low- $x$  sea and gluon distributions, whereas the fixed target data have determined the valence distributions. Now that high- $Q^2$  HERA data on NC and CC  $e^+p$  and  $e^-p$  inclusive double differential cross-sections are available, PDF fits can be made to HERA data alone, since the HERA high  $Q^2$  cross-section data can be used to determine the valence distributions. This has the advantage that it eliminates the need for heavy target corrections, which must be applied to the  $\nu$ -Fe and  $\mu D$  fixed target data. Furthermore there is no need to assume isospin symmetry, i.e. that  $d$  in the proton is the same as  $u$  in the neutron, since the  $d$  distribution can be obtained directly from CC  $e^+p$  data.

The ZEUS-JETS PDF fit [5] was an NLO QCD fit in the DGLAP formalism to ZEUS inclusive cross-section data and jet production data from HERA-I. The PDFs were parametrized at  $Q_0^2 = 7\text{GeV}^2$  by the form  $xf(x) = p_1 x^{p_2} (1 - x)^{p_3} (1 + p_4 x)$ , using 11 free parameters. Predictions for the cross-sections were made by evolving the PDFs to the  $Q^2$  values of the measurements and convoluting them with coefficient functions, calculated in the general mass variable flavour-number scheme of Thorne and Roberts [13], to produce structure function predictions. Predictions for jet cross-sections were made using NLO programmes [6, 7]. In evaluating the uncertainty on the PDF parameters and the cross-section predictions which derive from them full account is taken of correlated experimental uncertainties using the Offset method. However the determinations of the valence PDFs from HERA-I data are not as accurate as those from global fits because of poor statistics at high- $x$ . The addition of data from HERA-II changes this situation. In order to assess the impact of this new data the

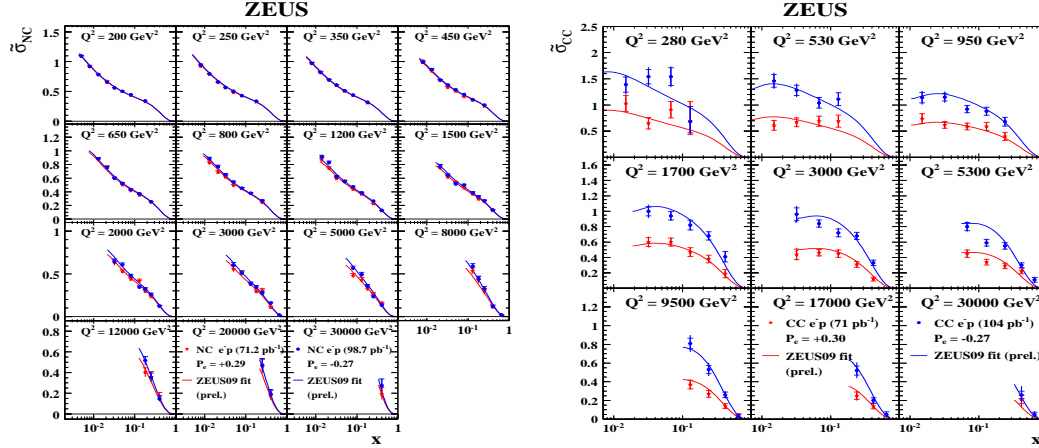


Figure 1: ZEUS NC (left-hand side) and CC (right-hand side)  $e^-p$  data from HERA-II running with polarised beams. The predictions of the ZEUS09 fit are superimposed

fit formalism has not been changed. This paper describes the improvement to the valence PDFs from adding ZEUS  $e^-p$  NC [8] from the 2005-6 running period,  $e^-p$  CC [9] data from the 2004-6 running period, and  $e^+p$  CC data [10] from the 2006-7 running period, into the ZEUS-JETS fit.

The polarization of the HERA-II data can also be exploited to measure electroweak couplings. The CC cross-sections give information on the propagator mass and the weak coupling. The NC cross-sections give information on the quark couplings to  $Z^0$ . A preliminary model independent extraction of these parameters was given in Ref [11] and will be updated when the full HERA-II data set is available. In the present paper we compare our data to the electro-weak predictions of the Standard Model.

Most of the data collected at HERA were for collisions between  $e^\pm$  of 27.5 GeV with protons of 920 GeV beam energies. During the final running period, HERA provided lower  $Q^2$  data ( $24 < Q^2 < 110 \text{ GeV}^2$ ), with modified trigger conditions, collected at three different proton beam energies (920, 575, 460 GeV). These data access high- $y$  and have been used to measure the longitudinal structure function  $F_L$  [12]. At low- $x$ , NLO QCD in the DGLAP formalism predicts that this structure function is strongly related to the gluon PDF. The reduced cross-section data from these runs have also been added into the ZEUS-JETS PDF fit and this provides an improved determination of the sea and gluon PDFs at small- $x$ . The new fit including all these new data is called the ZEUS09 PDF fit.

## 2 Results

Fig 1 (left-hand side) shows ZEUS data on NC  $e^-p$  double differential cross-sections from the 2005-2006 running period. There are  $99 \text{ pb}^{-1}$  of negatively polarised data ( $P_e = -0.27$ ) and  $71 \text{ pb}^{-1}$  of positively polarised data ( $P_e = +0.29$ ). This figure (right-hand side) also shows ZEUS data on CC  $e^-p$  double differential cross-sections from the 2004-2006 running period. There are  $104 \text{ pb}^{-1}$  of negatively polarised data ( $P_e = -0.27$ ) and  $71 \text{ pb}^{-1}$  of positively polarised data ( $P_e = +0.30$ ). Fig 2 (left-hand side) shows ZEUS data on CC  $e^+p$  double differential cross-sections from the 2006-2007 running period. There are  $56 \text{ pb}^{-1}$  of negatively polarised data ( $P_e = -0.36$ ) and  $76 \text{ pb}^{-1}$  of positively polarised data ( $P_e = +0.33$ ). The

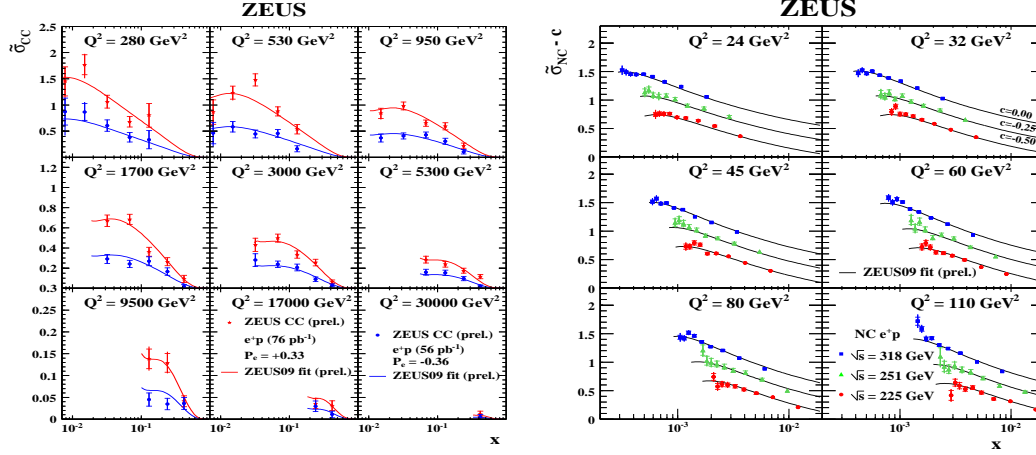


Figure 2: ZEUS CC  $e^+p$  data from HERA-II running with polarised beams (left-hand side). ZEUS NC  $e^+p$  data from 2007 HERA-II running with three different proton beam energies (right-hand side). The predictions of the ZEUS09 fit are superimposed

same figure (right-hand side) shows ZEUS data on NC  $e^+p$  double differential cross-sections for three proton beam energies corresponding to,  $\sqrt{s} = 318, 251, 225$  GeV, from the 2007 running period. There are 44.5, 7.1, 14.0 pb $^{-1}$  of data for each beam energy respectively. After the addition of these new data the 577 data points in the ZEUS-JETS PDF fit has increased to 1060 data points in the new ZEUS09 PDF fit. The results of this ZEUS09 fit are superimposed on the data in all these figures. The  $\chi^2$  per degree of freedom of this fit is 0.97. The agreement of all of the polarised data with the fit is a confirmation not only of the validity of the NLO QCD in the DGLAP formalism but also of the electroweak predictions of the Standard Model in a space-like process.

Fig. 3 (left-hand-side) illustrates the further impact of adding these new data by comparing the fractional uncertainties of the PDFs extracted from a fit including these data with those extracted from the ZEUS-JETS PDF. The improvement in the  $u$ -valence quark at high  $x$  comes from the addition of the NC and CC  $e^-p$  data from the 2004-2006 running. Both these processes are  $u$  quark dominated at large  $x$ . The  $d$ -valence quark uncertainty is also reduced significantly at large  $x$ . This improvement derives from the CC  $e^+p$  data which are  $d$  quark dominated at large  $x$ . Finally the improvement in the low- $x$  gluon and sea PDFs come from the addition of the NC  $e^+p$  lower  $Q^2$  data run at three different beam energies. This final addition of data completes the ZEUS09 PDF fit. The low- $x$  scale of the figure is extended to illustrate the improvement which is expected from adding these high- $y$  data. The PDFs extracted from the ZEUS09 fit are also compared to those of the ZEUS-JETS fit in Fig 3 (right-hand side). The central values of the fit are very compatible with the ZEUS-JETS fit, but the gluon PDF is a little steeper indicating the impact of the low- $Q^2$  data on the gluon PDF.

### 3 Summary

The inclusion of high- $Q^2$  NC and CC  $e^-p$  data into the ZEUS-JETS PDF fit results in an improved determination of the  $u$ -valence PDF. The further inclusion of high- $Q^2$  CC  $e^+p$  data results in an improved determination of the  $d$ -valence PDF. These data were run with

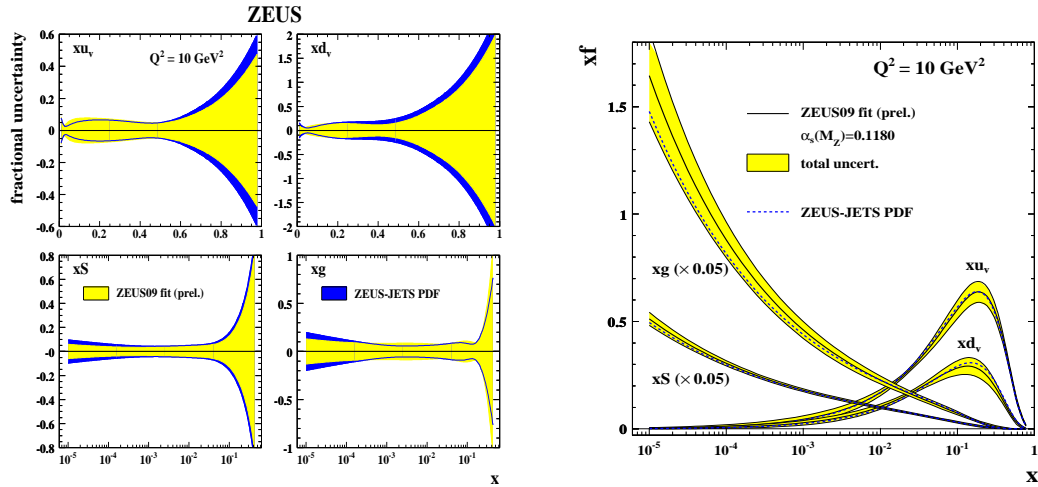


Figure 3: Left hand side: The fractional uncertainties of the ZEUS09 PDFs compared to those of the ZEUS-JETS PDFs. Right hand side: The PDFs extracted from the ZEUS09 fit compared to the ZEUS-JETS fit at  $Q^2 = 10 \text{ GeV}^2$ .

polarised lepton beams and the cross-section data for the different polarisations provides a spectacular confirmation of the Standard Model electroweak predictions in a space-like process. Finally the inclusion of lower- $Q^2$  data run at three different proton beam energies yields an improved determination of the low- $x$  sea and gluon PDFs. The new fit including all these data is called the ZEUS09 PDF fit [1].

## 4 Bibliography

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